The Spectacular Undular Bore in Iowa on 2 October 2007

TIMOTHY A. COLEMAN AND KEVIN R. KNUPP

Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama

DARYL HERZMANN

Department of Agronomy, Iowa State University, Ames, Iowa

(Manuscript received 9 January 2008, in final form 20 June 2008)

ABSTRACT

A visually impressive undular bore moved across much of Iowa on 2 October 2007, and video animations were captured by numerous Webcams. The bore was sampled very well by Doppler radar at close range, and also by the high-density mesoscale network of surface stations in place over Iowa and 1-min Automated Surface Observing System (ASOS) surface data at Des Moines, Iowa. Radar and surface observations are presented, along with a brief analysis of the structure of the bore.

1. Introduction

High-quality, ground-based photography of the cloud formations associated with atmospheric bores has not been widely available in the literature, even since these bores became well documented (e.g., Clarke 1972; Christie et al. 1978; Clarke et al. 1981; Crook 1986; Rottman and Simpson 1989). There have been some exceptions. One example is the "Morning Glory" of the Gulf of Carpentaria in Australia, which has been well photographed (e.g., Clarke et al. 1981; Smith et al. 1982). A photograph of the wave cloud associated with an undular bore approaching Norman, Oklahoma, was published by Mahapatra et al. (1991). Also, Wakimoto and Kingsmill (1995) show photographs of an undular bore generated by the collision of a sea-breeze front and a gust front in Florida. In the present case, the bore was in advance of an active mesoscale convective system (MCS).

With the advent of nearly continuously operating video cameras such as "towercams" and "Webcams," deployed by numerous public and private interests over the past few years, photographs of many atmospheric phenomena have become more frequent. Such a case occurred on 2 October 2007, when an atmospheric undular bore propagated across much of central and eastern Iowa. This bore was apparently generated by the interaction of cool, MCS-generated density current outflow with a very stable low-level inversion. The distinctive cloud bands associated with this bore were captured on video by at least three Webcams, operated by the Iowa Environmental Mesonet of Iowa State University in partnership with KCCI-TV of Des Moines, Iowa—a private and public sector partnership known as the "SchoolNet8 Project" (Fig. 1). The time lapse photography, along with detailed radar and 1-min surface observations, and operational numerical model output, allow for excellent observations and analysis of the bore.

In this note, the environment in which this bore formed is examined in section 2. Meteorological measurements of the bore, including Doppler radar data and surface measurements, along with a brief analysis, are presented in section 3. Conclusions are presented in section 4.

2. Environment

A 500-hPa trough advanced slowly eastward through the northern Rocky Mountain states during the 12-h

Corresponding author address: Tim Coleman, Department of Atmospheric Science, University of Alabama in Huntsville, NSSTC, 320 Sparkman Dr., Huntsville, AL 35805.
E-mail: coleman@nsstc.uah.edu

DOI: 10.1175/2008MWR2518.1

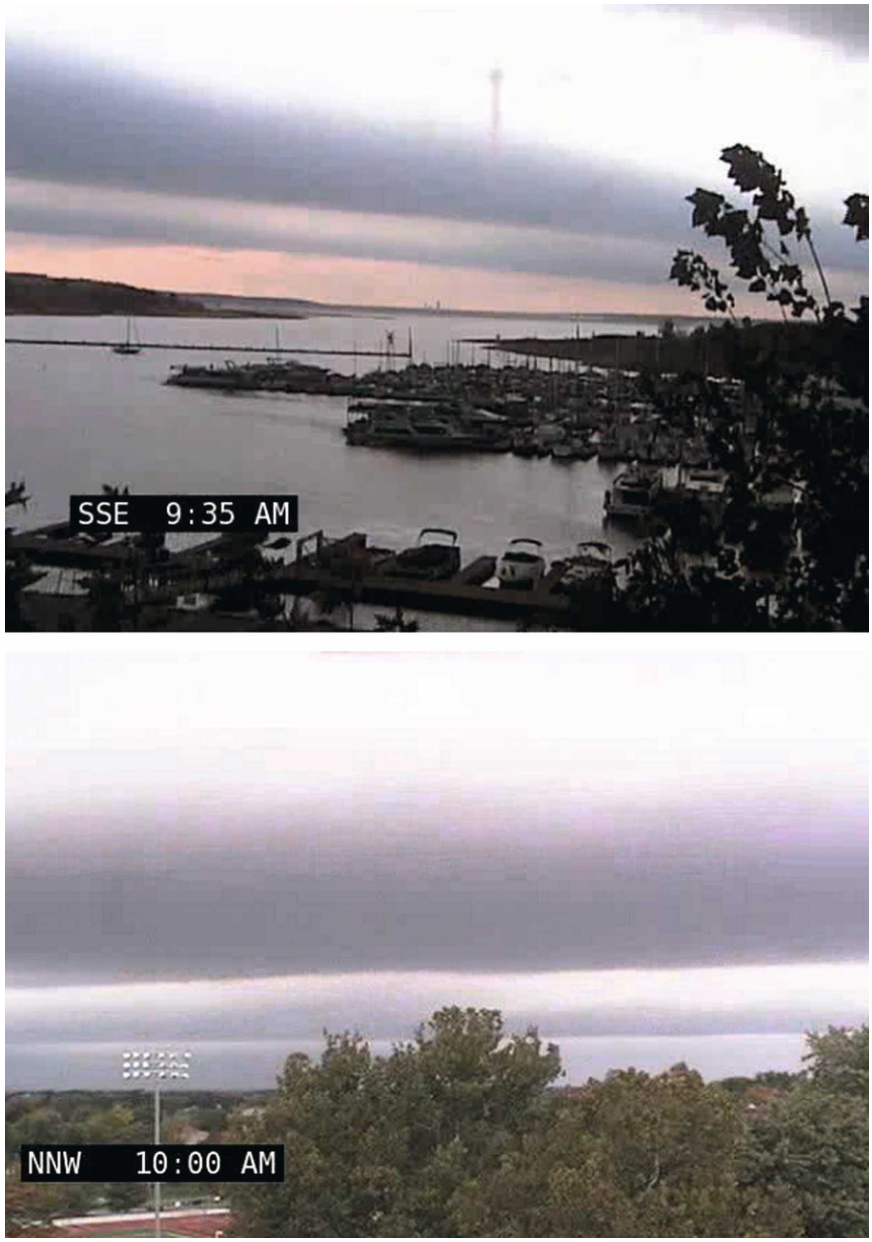

FIG. 1. Photographs of clouds associated with undular bore captured from videos taken by two Iowa Environmental Mesonet/KCCI-TV Schoolnet 8 Webcams; (top) looking SSE at Saylorville Lake, IA, at 1435 UTC (0935 CDT), and (bottom) looking NNW at Indianola, IA, at 1500 UTC (1000 CDT).). See Fig. 2 for the locations of these cameras. (Animations from these and an additional Webcam at Tama, IA, are located online at http://vortex.nsstc.uah.edu/~coleman/Iowabore.)

period leading up to 1200 UTC 2 October 2007. A surface cold front was also associated with the trough, and was located from North Dakota into Nebraska at 1200 UTC 2 October. Scattered showers were located over parts of Kansas at 0600 UTC, then increased in intensity and aerial coverage over Kansas and Nebraska between 0600 and 1000 UTC. The convective activity organized into a MCS between 0900 and 1300 UTC, extending from western Iowa into eastern Nebraska and western Kansas at 1300 UTC. This occurred in an environment featuring rather weak instability but strong low-level wind shear. A radar presentation at 1300 UTC, 1.5–2 h prior to the pictures shown in Fig. 1, is presented in Fig. 2. With strong southwesterly flow at

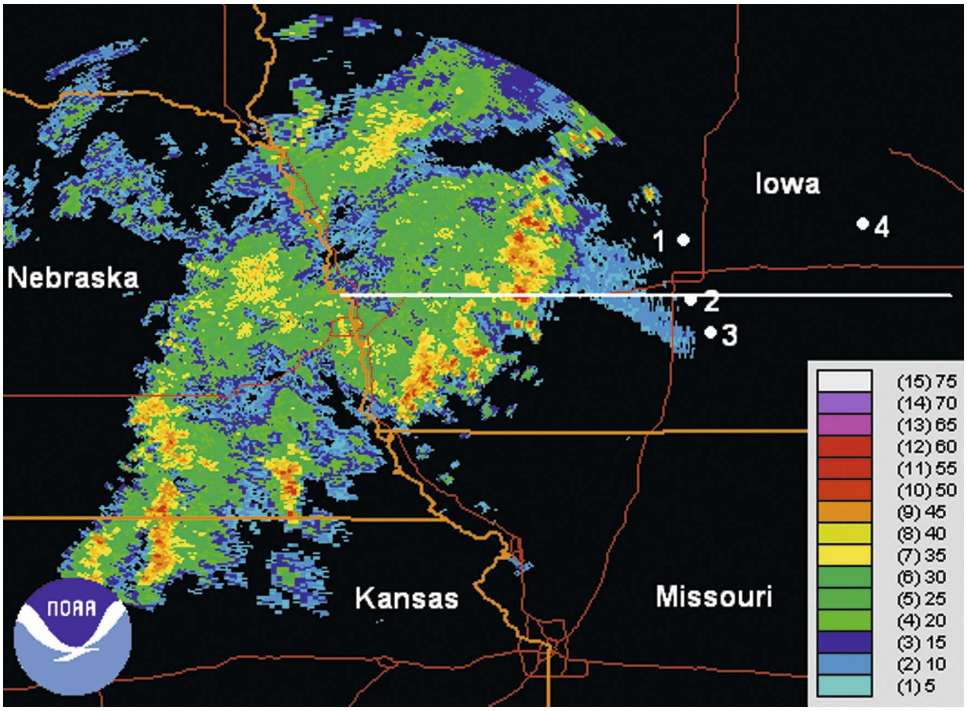

FIG. 2. The 0.5° elevation base reflectivity (dBZ) from the Omaha, NE (KOAX), WSR-88D radar at 1300 UTC 2 Oct 2007. Approximate locations of Webcams (W) and surface stations (S) are noted as follows: 1) Saylorville Lake (W); 2) Des Moines (S); 3) Indianola (W); 4) Tama (W). Latitude 41.5°N (see Fig. 3) is indicated by the white east–west-oriented line.

850–700 hPa, the northeast–southwest-oriented leading band of convection only slowly advanced eastward over Iowa between 1200 and 1600 UTC. As it did so, it encountered a very stable low-level inversion over eastern Iowa. *A density current impinging on a low-level stable layer is a common scenario for the initiation of atmospheric bores* (e.g., Simpson 1997). The cool outflow density current associated with the approaching MCS likely initiated the bore upon interaction with the low-level inversion over central and eastern Iowa.

An east–west cross-section analysis of 12-km North American Model (NAM) data, from National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) along latitude 41.5°N at 1500 UTC shows the low-level inversion layer over eastern Iowa very clearly. Temperatures (>20°C) occurred near 1 km MSL (Fig. 3a). A layer of very high static stability, as indicated by large values of the Brunt–Väisälä frequency N (Fig. 3b), extended eastward from latitude 94.5°W, below 1 km MSL. Based on this analysis, and a Mesoscale Analysis and Prediction System (MAPS) sounding analysis at Des Moines, Iowa, at 1400 UTC (Fig. 4), the height of the surface inversion layer ahead of the MCS was near 1 km MSL, so the depth of the inversion layer before bore passage was $h_0 = 700$ m AGL. Unfortunately, no actual upper-air observation is available at Des Moines, with the closest sounding to the west at Omaha, Nebraska (OAX), and the closest sounding to the east at Davenport, Iowa (DVN), both more than 150 km from Des Moines. So, some uncertainty exists with the MAPS sounding in Fig. 4.

The inversion was also topped by a much less stable layer above about 1 km MSL, which provided a duct for gravity wave energy (e.g., Lindzen and Tung 1976; Nappo 2002). Such a ducting or wave-trapping mechanism may be necessary for a bore to propagate over a significant distance (e.g., Crook 1986). Atmospheric waves may be reflected by layers with large vertical gradients of m^2 (where m is the vertical wavenumber), and are totally reflected by layers where $m^2 < 0$ (e.g., Gill 1982; Nappo 2002). Here m^2 is related to the Scorer parameter l^2 (Scorer 1949) through $m^2 = l^2 - k^2$, where k is the horizontal wavenumber ($k = 2\pi/\lambda$). The Scorer parameter used herein is

$$l^2 = \frac{N^2}{(c-U)^2} + \frac{\dfrac{\partial^2 U}{\partial z^2}}{(c-U)}, \qquad (1)$$

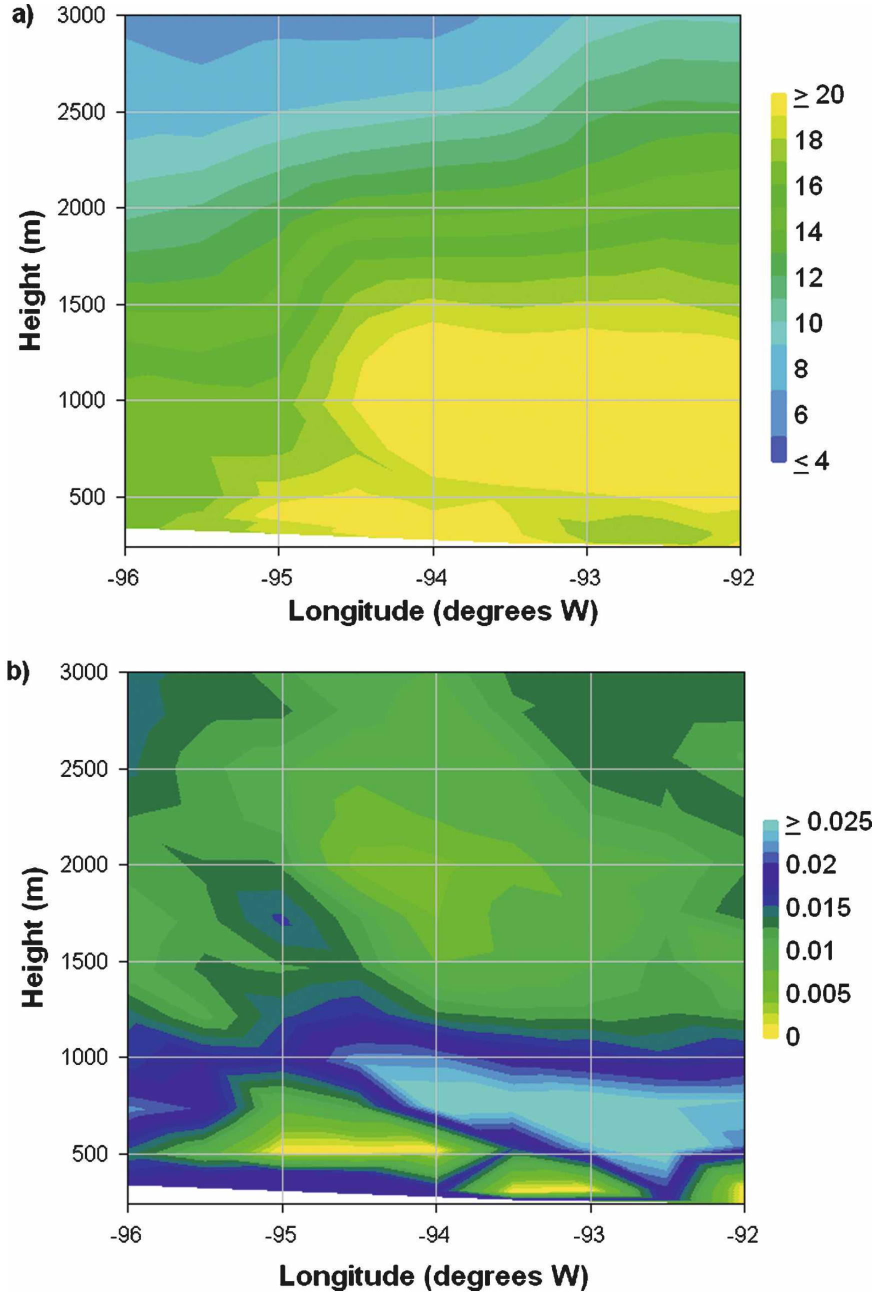

FIG. 3. NAM model east–west cross section along 41.5°N latitude of (a) temperature (°C) and (b) N (s^{-1}) at 1500 UTC 2 Oct 2007. The corridor containing Saylorville Lake, Des Moines, and Indianaola is near longitude 93.7°W.

where N is the Brunt–Väisälä frequency, U is the component of the background wind in the direction of bore motion (from 300°), and c is the bore speed (12.8 m s^{-1}). So, $m^2 < 0$ implies that either the stability is small or negative, or there is significant curvature in the wave-normal wind profile. As defined by Lindzen and Tung (1976), the "reflection coefficient," r, for an upward-propagating wave incident on a reflecting layer, is the absolute value of A_1/B_1, where A_1 is the amplitude of the reflected wave and B_1 is the amplitude of the incident wave. Following the analysis of Nappo (2002), $m^2 < 0$ in the reflecting layer implies that $r = 1$ for nontrivial cases, meaning that waves incident on the reflecting layer with $m^2 < 0$ from below are perfectly reflected, forming a wave duct.

Using smoothed and interpolated NAM model data

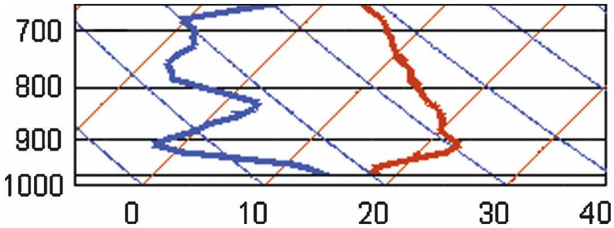

FIG. 4. Skew-T ln$p$ diagram of sounding analysis from MAPS model at Des Moines, Iowa (KDSM), at 1400 UTC 2 Oct 2007.

from 1500 UTC, along with the observed horizontal wavelength of 7 km, a vertical profile of m^2 was constructed (Fig. 5). A deep layer with $m^2 < 0$ is present from 900 m MSL to near 1500 m MSL, associated with a rapid decrease in static stability above 900 m MSL, and with curvature in the wind profile near a jet at 900 hPa. This layer prevented significant upward energy loss due to vertical wave propagation, and provided an excellent wave duct.

3. Observations and analysis

a. Surface observations

One characteristic phenomenon associated with the passage of an undular bore at a surface station is a sudden rise in pressure (e.g., Koch et al. 1991; Karyampudi et al. 1995). This rise is related hydrostatically to the rapid increase in the depth of the low-level cool stable layer, associated with dry-adiabatic lifting below the lifted condensation level (LCL). The initial pressure increase in an *undular* bore is typically followed by fluctuations in surface pressure, oscillating at the same period as the waves atop the deepened cool layer. However, with a bore, the overall pressure rise is not transient (as with gravity waves or solitary waves); the change in stable-layer depth, and associated surface pressure, remains elevated for a longer period of time. Locatelli et al. (1998) refer to the change in depth as "relatively permanent."

In the 2 October 2007 case, with 300-hPa divergence and low-level warm advection over Iowa, surface pressures were falling on a synoptic-scale across Iowa during the morning hours. Averaging the observations between 0800 and 1430 UTC at Des Moines (KDSM) shows a background pressure tendency about -0.91 hPa h^{-1}, which continues into the afternoon (Fig. 6). This tendency is removed from the pressure time series to isolate the pressure fluctuations associated with the bore.

The 1-min time series of pressure perturbations (p') at KDSM from 1415 to 1515 UTC (Fig. 7a) clearly show the pressure jump associated with bore passage. After a small drop in p' just ahead of the bore, there was a rapid rise in pressure of about 1.5 hPa in 9 min (1432–1441 UTC). Two more pressure oscillations followed the initial pressure jump, both with periods about 8 min and amplitudes of 0.20–0.25 hPa.

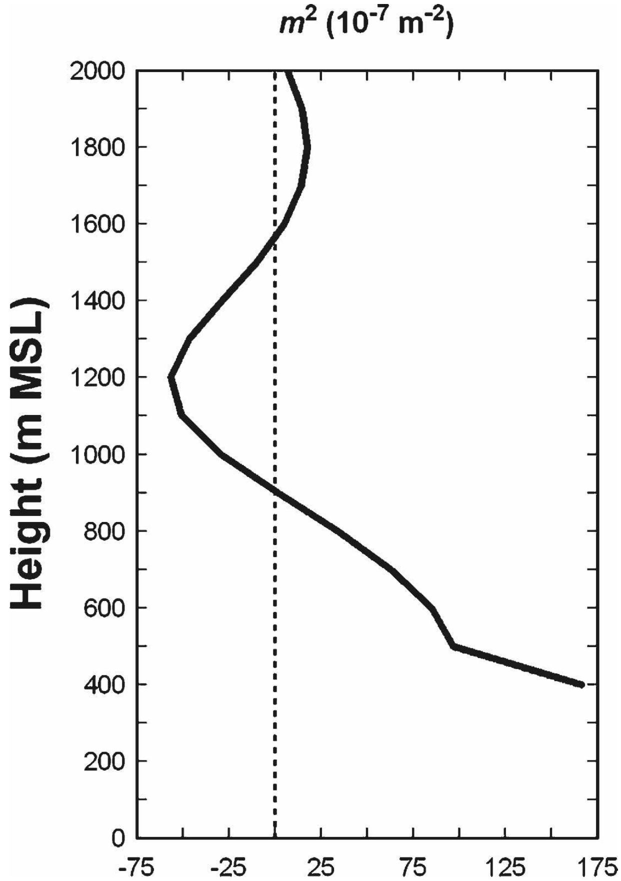

FIG. 5. Vertical profile of m^2 (10^{-7} m^{-2}) based on NAM data at 1500 UTC. The dashed vertical line indicates $m^2 = 0$.

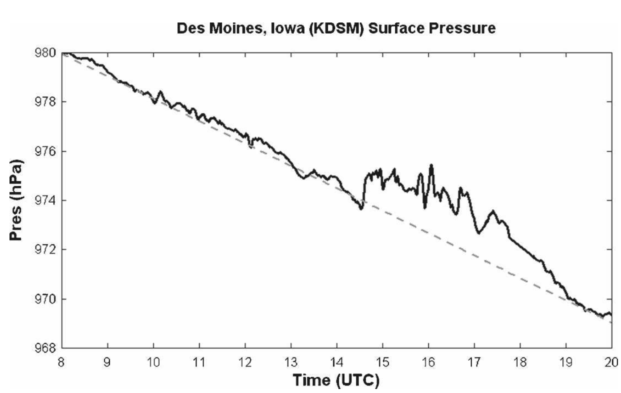

FIG. 6. Surface pressure (hPa, solid) at Des Moines, 0800–2000 UTC 2 Oct 2007, and background pressure tendency of -0.91 hPa h^{-1} (dashed).

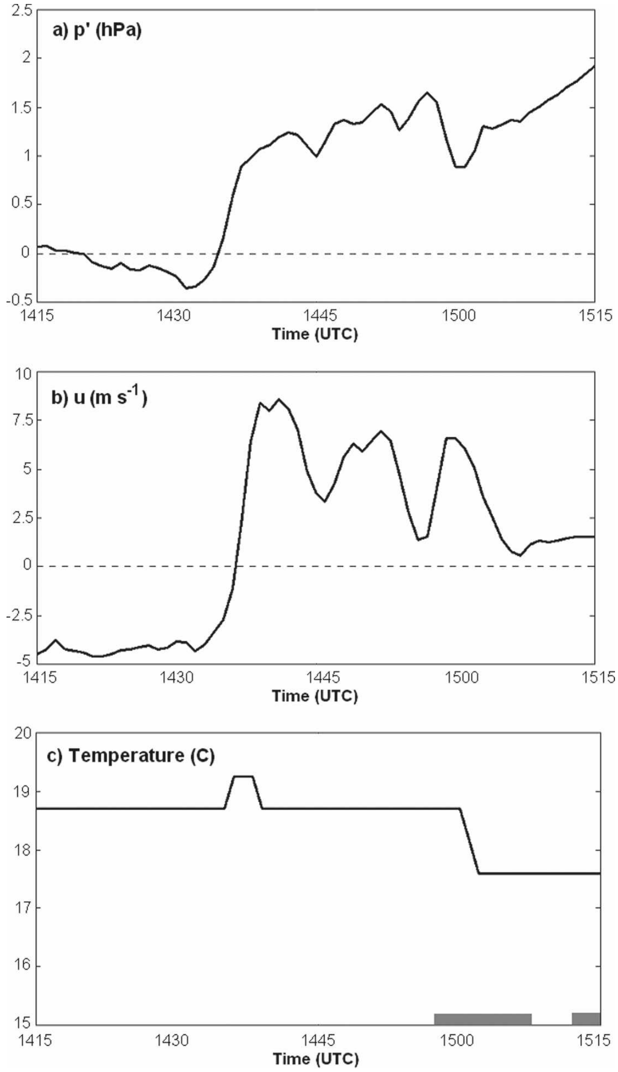

FIG. 7. The 1-min observations at Des Moines, 1415–1515 UTC 2 Oct 2007 of (a) pressure perturbation p' (hPa), (b) wind perturbation u (m s^{-1}, in direction of bore motion), and (c) temperature (°C). Times of rainfall are indicated in lower portion of (c) by gray-shaded bars.

Surface winds also rapidly fluctuated with bore passage. The component of the 2-min-averaged surface wind in the direction of observed bore motion (from 300° at 12.8 m s^{-1}) is plotted in Fig. 7b. As is typical for bores, the wind shifted to the direction of bore motion as it passed, increasing to 8.4 m s^{-1}. Oscillations in bore-normal wind also occurred behind the initial wind shift, with periods around 9 min and amplitudes of 2–3 m s^{-1}. It should be noted that the maximum bore-normal wind observed is 8.4 m s^{-1}; even though radar observations show slightly higher values, they are still less than 12.8 m s^{-1}. This provides evidence that this feature is not a density current, since there is typically rear-to-front flow in density currents, which exceeds the speed of movement (e.g., Simpson 1997).

The 1-min surface temperature observations are shown in Fig. 7c. Note that surface temperatures remained basically constant throughout the passage of the bore, with the exception of a slight (0.5°C) temperature rise at the same time as the initial pressure jump. This could be attributed to measurement noise, or it may be associated with the downward mixing of slightly warmer air in the stable boundary layer as the bore and associated gusty winds pass by. *The lack of any temperature drop associated with the pressure rise provides strong evidence that this feature is not a density current*, since the temperature difference between the cold air behind a density current and the environment ahead of it is what causes the movement of the density current (e.g., Simpson 1997). The 1°C temperature drop just after 1500 UTC was coincident with the onset of heavy rain at the observation site.

b. Radar observations

The initial band of vertical motion associated with the bore produced a "fine line," with maximum reflectivities >25 dBZ, in plan position indicator (PPI) reflectivity scans from the Des Moines, Iowa (KDMX) Weather Surveillance Radar-1988 Doppler (WSR-88D) Doppler radar (Fig. 8a). This indicates that the bore may have produced some light precipitation. The bore, including three wavelengths of the waves generated behind it, is clearly visible in PPI base velocity scans from KDMX (Fig. 8b).

The 1450 UTC Doppler velocity cross sections at 140° azimuth from the KDMX radar offer a more detailed analysis of the kinematics of the bore (Fig. 8c). Doppler velocities from PPI scans at various elevation angles were gridded (resolution 1 km horizontal, 200 m vertical). The main wind shift at the leading edge of the bore is apparent, with radial velocities shifting from inbound near the 29-km range to outbound, at speeds >10 m s^{-1}, near the 26-km range. The waves behind the leading edge of the bore are also apparent, with at least two more regions of outbound radial velocities centered at ranges of 19 and 12 km, flanked by inbound velocities.

Applying finite differencing ($\delta \mathbf{V}_r/\delta r$), where $\mathbf{V}_r$ is the radial velocity and r is the range from the radar, to the gridded 1450 UTC Doppler velocity data along 140° azimuth, 2D convergence was estimated. Upward integration of the continuity equation allowed for estimates of vertical motion, assuming that convergence occurred only along the radar beam, which was roughly normal to bore motion. The radar cross-section values of hori-

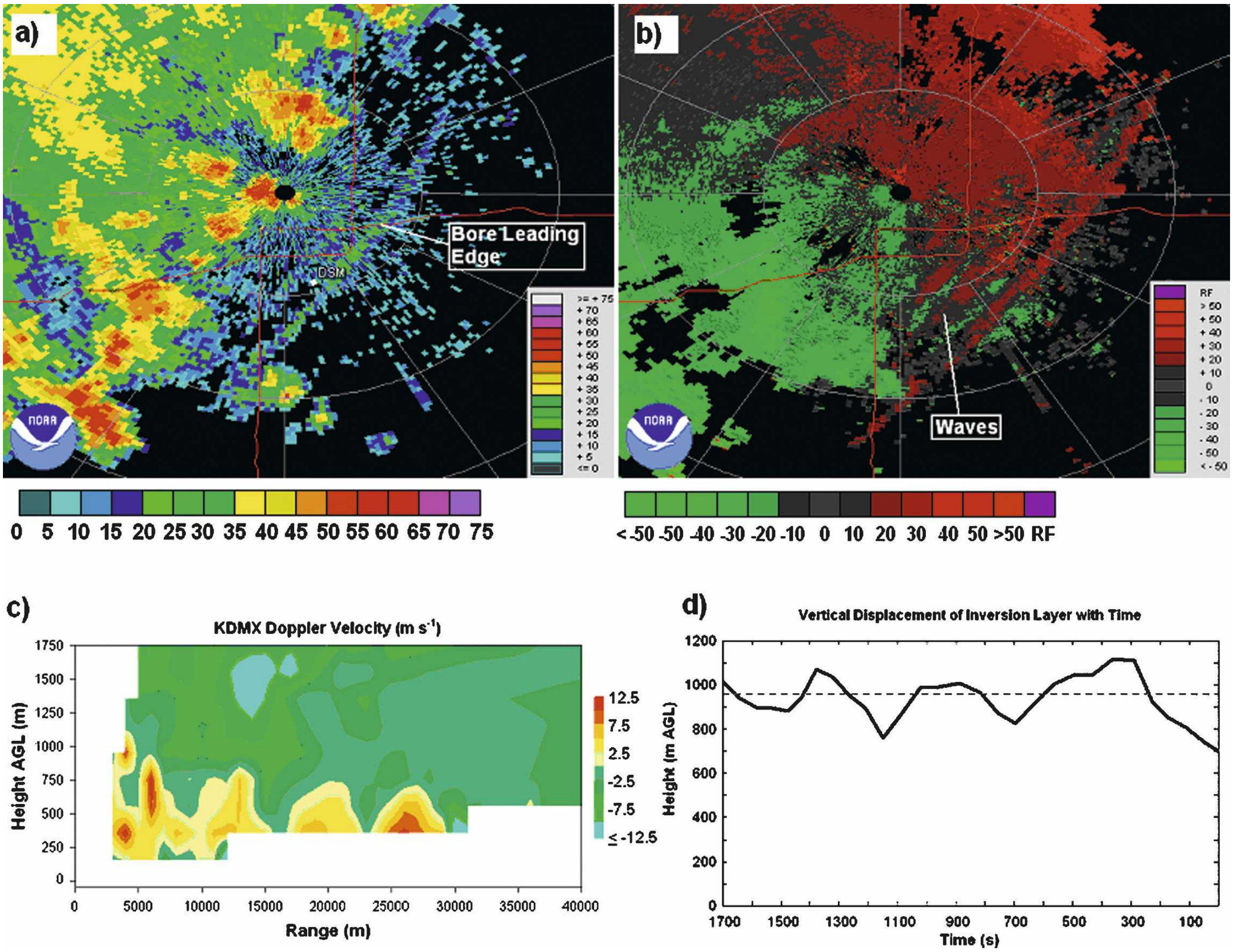

FIG. 8. (a) The 0.5° elevation reflectivity scan from the KDMX WSR-88D at 1441 UTC, (b) 0.4° elevation Doppler velocity scan from KDMX at 1458 UTC, (c) velocity cross section at 140° azimuth from KDMX at 1450 UTC, and (d) analyzed vertical displacement of the top of the stable boundary layer with time, based on kinematics at 1450 UTC (see text).

zontal wind and analyzed vertical motion at 1450 UTC, along with bore speed, were utilized to estimate a time series of vertical displacement of the top of the stable inversion layer through the bore, making the assumption that the bore was in a steady state (Fig. 8d). This analysis was performed using rough trajectory calculations. This analysis indicates that the top of the boundary layer was displaced upward about 400 m in 300 s, then oscillated to about an average height of 958 m after the leading edge of the bore passed.

c. *Analysis*

The 1-min Automated Surface Observing System (ASOS) data available from Des Moines, along with the high-resolution Doppler radar imagery of the bore, which passed directly over the KDMX WSR-88D radar, allow for excellent analysis of the characteristics of the bore. These may be compared with theory.

As stated in section 2, the height of the prebore stable boundary layer on 2 October 2007 was $h_0 = 700$ m AGL. The height of the boundary layer after bore passage, h_1, may be estimated using the vertical displacement calculations described in section 3b. These calculations indicate that the average height of the boundary layer behind the leading edge of the bore was 958 m AGL. PPI scans of velocity indicate that oscillations in velocity associated with the bore occurred as high as 900–1100 m AGL. So, using an average from the two methods, h_1 is estimated at 1000 m AGL. This implies a bore strength (h_1/h_0) of 1.43. According to Simpson (1997), when the bore strength is between 1 and 2, the bore is undular, as is the case here.

The theoretical bore speed may be determined based on the bore strength and the theoretical speed for an internal gravity wave in the surface based layer (C_{gw}).

Here C_{gw}, based on shallow-water theory, may be written as (Simpson 1997; Knupp 2006)

$$C_{gw} = \left[g\left(\frac{\Delta\theta_v}{\theta_v}\right)h_0\right]^{1/2}, \tag{2}$$

where $\Delta\theta_v$ is the difference in average θ_v between the lower stable layer and the upper layer, and h_0 is the depth of the stable layer. The quantity $g(\Delta\theta_v/\theta_v)$ is an expression for the "reduced gravity" (e.g., Simpson 1997). In this case, $C_{gw} = 11.24$ m s^{-1}.

The bore speed (C_{bore}) is then (Rottman and Simpson 1989)

$$C_{bore} = C_{gw}\left[\frac{1}{2}\frac{h_1}{h_0}\left(1+\frac{h_1}{h_0}\right)\right]^{1/2}, \tag{3}$$

where h_1 is the depth of the stable layer after bore passage. This provides $C_{bore} = 14.8$ m s^{-1} in this case. In the 2 October 2007 case, the bore was moving from 300° azimuth, and the NAM model soundings indicated an average bore-normal wind of -2.5 m s^{-1} in the 0–700 m AGL layer. Since C_{bore} assumes no background flow, the actual theoretical speed of the bore is 12.3 m s^{-1}, close to the observed 12.8 m s^{-1}.

The observed wavelengths of the waves behind the bore were determined using radar data, and were about 7 km. Laboratory experiments done by Rottman and Simpson (1989) and atmospheric measurements by Clarke et al. (1981) indicate that, for bore strengths between 1.0 and 2.0, the horizontal wavelength of the waves behind the bore should be about 10 ($\pm$4) $\times$ h_1. In this case, $h_1 = 1000$ m, so the wavelength should be around 6–14 km. Therefore, the observed wavelength of 7 km is consistent with this theory.

4. Conclusions

An intense atmospheric undular bore was initiated over central Iowa on 2 October 2007, as an MCS interacted with a stable low-level inversion. A less stable layer was in place above the inversion, allowing for the ducting of wave energy and bore maintenance.

Photographs (shown) and videos (referenced online, see Fig. 1) of the cloud features associated with the bore were dramatic. The 1-min surface data were available from the ASOS at Des Moines, and the bore also moved directly over the Des Moines WSR-88D Doppler radar. These datasets allowed a simple analysis of the kinematics of the bore and comparison with theory.

Removal of the background synoptic pressure falls revealed that the bore caused a rapid rise in surface pressure, followed by pressure oscillations. Rapid changes in surface winds were also observed.

The vertical motion at the leading edge of the bore produced a "fine line" in PPI radar reflectivity scans, but the bore and its multiple wavelengths of oscillations were more apparent in Doppler velocity measurements. Analysis of Doppler velocity data allowed for estimates of the upward displacement and undulations of the top of the low-level stable layer, and assessment of bore strength, which was 1.43 in this case, consistent with the bore's undular nature.

The vertical displacement of the low-level stable layer, in conjunction with model sounding data, allowed for the calculation of theoretical bore speed, which was within 10% of the observed bore speed. Laboratory results from the literature comparing the horizontal wavelength of the waves behind the bore, with the average height of the stable layer after bore passage, were also consistent with the wavelengths observed in this case.

Acknowledgments. The authors wish to thank KCCI-TV in Des Moines, Iowa, as well as CIPCO and Touchstone Energy for their sponsorship of the "Schoolnet8 Project." The authors also thank the anonymous reviewers, whose comments significantly improved this paper. Funding for this research was provided by the National Science Foundation (Grant ATM-0533596), as part of the Atmospheric Boundary Initiation and Delineation Experiment (ABIDE).

REFERENCES

Christie, D. R., K. J. Muirhead, and A. L. Hales, 1978: On solitary waves in the atmosphere. *J. Atmos. Sci.,* **35,** 805–825.

Clarke, R. H., 1972: The Morning Glory: An atmospheric hydraulic jump. *J. Appl. Meteor.,* **11,** 304–311.

——, R. K. Smith, and D. G. Reid, 1981: The Morning Glory of the Gulf of Carpentaria: An atmospheric undular bore. *Mon. Wea. Rev.,* **109,** 1726–1750.

Crook, N. A., 1986: The effect of ambient stratification and moisture on the motion of atmospheric undular bores. *J. Atmos. Sci.,* **43,** 171–181.

Gill, A. E., 1982: *Atmosphere–Ocean Dynamics*. Academic Press, 662 pp.

Karyampudi, V. M., S. E. Koch, C. Chen, J. W. Rottman, and M. L. Kaplan, 1995: The influence of the Rocky Mountains on the 13–14 April 1986 severe weather outbreak. Part II: Evolution of a prefrontal bore and its role in triggering a squall line. *Mon. Wea. Rev.,* **123,** 1423–1446.

Knupp, K. R., 2006: Observational analysis of a gust front to bore to solitary wave transition within an evolving nocturnal boundary layer. *J. Atmos. Sci.,* **63,** 2016–2035.

Koch, S. E., P. B. Dorian, R. Ferrare, S. Melfi, W. C. Skillman, and D. Whiteman, 1991: Structure of an internal bore and dissipating gravity current as revealed by Raman Lidar. *Mon. Wea. Rev.,* **119,** 857–887.

Lindzen, R. S., and K.-K. Tung, 1976: Banded convective activity and ducted gravity waves. *Mon. Wea. Rev.,* **104,** 1602–1617.

Locatelli, J. D., M. T. Stoelinga, P. V. Hobbs, and J. Johnson, 1998: Structure and evolution of an undular bore on the High Plains and its effects on migrating birds. *Bull. Amer. Meteor. Soc.,* **79,** 1043–1060.

Mahapatra, P. R., R. J. Doviak, and D. S. Zrnic, 1991: Multisensor observation of an atmospheric undular bore. *Bull. Amer. Meteor. Soc.,* **72,** 1468–1480.

Nappo, C. J., 2002: *An Introduction to Atmospheric Gravity Waves.* Academic Press, 276 pp.

Rottman, J. W., and J. E. Simpson, 1989: The formation of internal bores in the atmosphere: A laboratory model. *Quart. J. Roy. Meteor. Soc.,* **115,** 941–963.

Scorer, R. S., 1949: Theory of waves in the lee of mountains. *Quart. J. Roy. Meteor. Soc.,* **75,** 41–56.

Simpson, J. E., 1997: *Gravity Currents: In the Environment and the Laboratory.* 2nd ed. Cambridge University Press, 244 pp.

Smith, R. K., N. Crook, and G. Roff, 1982: The Morning Glory: An extraordinary atmospheric undular bore. *Quart. J. Roy. Meteor. Soc.,* **108,** 937–956.

Wakimoto, R. M., and D. E. Kingsmill, 1995: Structure of an atmospheric undular bore generated from colliding boundaries during CaPE. *Mon. Wea. Rev.,* **123,** 1374–1393.